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STUDIES FOR STUDENTS.

DEFORMATION OF ROCKS.¹

I. GENERAL.

Rock units under thrust act very differently, depending upon their thickness, strength, and other characters, upon the character and thickness of the rock units above and below, and upon the closeness of the folding.

It is believed that the outer part of the earth may be divided into three zones: (1) An upper zone of fracture; (2) a middle zone of combined fracture and plasticity; (3) a lower zone of plasticity.

(1) *Rocks under less weight than their ultimate strength when rapidly deformed are in the zone of fracture.* That is, when rocks under such conditions are deformed they break, and crevices small or great separate the broken parts. The fractured rocks may be jointed, faulted, or brecciated in a simple or complex manner. The fractures may be far apart and of great size and extent, or near together and of small size and extent. Innumerable parallel fractures may occur in the same direction when, as shown in a subsequent paper, the rocks develop a parting or fissility. In extreme cases of fracture the rocks become autoclastic or are broken into innumerable fragments by the forces of deformation. These

¹ Published by permission of the Director of the United States Geological Survey. In the preparation of this series of papers I have been greatly assisted by PROFESSOR L. M. HOSKINS. In the Sixteenth Annual Report of the United States Geological Survey, where my entire paper will appear, PROFESSOR HOSKINS's work, from which extracts are below made, will also be published. To WILLIS's paper upon the Appalachians I am also greatly indebted. ("The Mechanics of Appalachian Structure," by BAILEY WILLIS, Thirteenth Ann. Rept. U. S. Geol. Surv., pp. 211-281.) I should also mention HEIM's great work, "Mechanismus der Gebirgsbildungen," from which I have absorbed many ideas.

fragments may be rounded, and such rocks resemble ordinary clastic rocks. In this case the rock becomes a pseudo-conglomerate, and there are all gradations between such a rock and one in which the cracks and crevices become subordinate, the deformation being chiefly that of flowage. For a soft shale, but a small thickness of superincumbent strata, possibly 500 meters or less, may prevent any considerable fractures and crevices from forming. For the strongest massive rocks, a great thickness of superincumbent strata, possibly nearly 10,000 meters, may be necessary to prevent cracks and crevices from forming.

Heim states that it is impossible for crevices and cracks to exist at so great a depth as 5000 meters.¹ From geological observations I have for some time been convinced that a greater depth than this is required to close crevices under some conditions. The depth at which a cavity of any definite size begins to close will depend upon its form, upon the strength of the rock, upon whether the rock is saturated with water, upon the increased plasticity of the rock due to the rise of temperature with increased depth, upon the amount of lateral thrust, and upon the length of time during which the rock is subjected to stress.

So large an opening as the St. Gothard tunnel, 6.4 meters high and 8 meters wide, exists with no observed tendency to close under an irregular dome of rock which for some distance is more than a mile thick and has a maximum thickness of 1830 meters. The thickness of the superincumbent rock diminishes from the maximum to nothing at the ends of the tunnel. However, it would appear from this case to be highly probable that in order to close cavities the maximum number must be multiplied by a factor of considerable magnitude.

It would seem that mathematicians and physicists, after experiments upon the plasticity of rocks of different kinds, ought to give an approximate solution of the problem as to the depth at which cavities in any kind of rock would begin to close. We need long continued experiments upon the plasticity of different rocks at various temperatures and pressures, and while the rocks

¹ *Mechanismus der Gebirgsbildungen*, by ALBERT HEIM, Band II., 1878, p. 110.

are saturated with superheated water. We also need a satisfactory theory of the flow of viscous liquids or plastic solids.

In the absence of these data a first approximate solution of the problem has been made by Professor L. M. Hoskins, of Stanford University, based upon the elastic limit and the ultimate strength of rocks. The most carefully conducted experiments agree with theory and seem to show that rock masses of the same form have the same crushing strength per unit of area whether in large or small masses. In experiments on cubes running from 1 to 12 inches in diameter,¹ in each set there are irregular variations per unit area on each side of the average, but these are probably explained by the unavoidable variations in the strength of the different pieces tested and the impossibility of obtaining exactly similar conditions.

Professor Hoskins, after a comprehensive discussion, reaches the following general conclusions upon the closing of cavities in rocks:

(I.) In any region if the three principal stresses of a rock mass are equal, a spherical cavity cannot exist permanently if the normal stress in the rock exceeds the pressure within the cavity by as much as two-thirds the elastic limit or the ultimate strength.

(II.) If two of the three principal stresses are equal, a cylindrical cavity of considerable length whose axis is parallel to the third direction cannot exist permanently if either of the equal principal stresses exceeds the interior pressure by as much as half the elastic limit or the ultimate strength, or if the third principal stress exceeds the interior pressure by as much as half the elastic limit or ultimate strength.

Although the discussion has been confined to these special cases, it seems safe to state the following general proposition as at least probably true:

(III.) No cavity can exist permanently in a rock throughout a considerable portion of which the normal stress in any direction exceeds the pressure within the cavity by as much as the elastic limit or ultimate strength of the rock.

Professor Hoskins further says that:

The intensity of stress upon a horizontal plane at any depth is equal to the weight of a column of rock of unit cross-section extending to the surface.

¹ Tests of metals and other materials for industrial purposes, made with the United States testing machine at Watertown Arsenal, Mass., by S. V. Benét, Chief of Ordnance. Rept. of Chief of Ordnance for year ending June 30, 1884, pp. 126, 166, 167 188-199, 212, Washington, 1886.

In applying these results to ascertain the depth at which cavities would close, the following additional assumptions are made: Some of the cavities are supposed to have a form best adapted to resist closing. In most cases, as shown by Professor Hoskins, this is probably spherical. The cavities are supposed to be very small as compared with their depth below the surface, so that the pressure due to gravity is practically the same for all parts of a cavity. The rocks are assumed as being among the strongest—that is, having a crushing strength of 1700 kilograms per square centimeter. This amount somewhat exceeds the average crushing strength of the ordinary crystalline rocks, such as granite and schist, but is surpassed by about one-fifth in some of the very strongest hornblende-granites and basic rocks. It is probable that the stronger, and perhaps the strongest, rocks should be chosen, for the minute cavities in the interstices are concerned, and these can only be closed by the crushing or flowing of the individual mineral particles. Upon the one hand it is natural to suppose that some of the minerals composing rocks are stronger than any rock. Upon the other hand the cavities may be largely closed by the flowage or fracture of the weaker minerals of a given rock. However this may be, for the purposes of the present discussion it is plain that sandstones are to be placed upon the same basis as quartzites, and possibly shales upon the same basis as slates and schists.

The specific gravity of the outer crust of the earth is assumed to be 2.7.¹ As openings in the earth are usually filled with water, in obtaining a maximum depth at which cavities can exist permanently, it is probably necessary to suppose that cavities are supported by the hydrostatic pressure of a column of water reaching to the surface, and therefore that 1 should be subtracted from the specific gravity of the rock in determining the depth at which the closing of cavities occurs. Under the slowly acting orogenic forces it is probable that the water must be

¹ This estimate of 2.7 was kindly furnished me by Mr. G. K. GILBERT as a close approximation to the specific gravity of the continental masses. It is the same as my own best guess of the specific gravity of the pre-Cambrian rocks.

considered as free to escape, and that the viscosity of water in minute crevices plays no part.

If it be supposed that the rocks above the cavities are solid to the surface, and therefore that they are not supported by the hydrostatic pressure of a column of water to the surface, the problem is reduced by Professor Hoskins' solution to finding the height of a column 1 square centimeter in area, with a specific gravity of 2.7, which weighs two-thirds of 1700 kilograms for Conclusion I., and weighs 1700 kilograms for Conclusion III. This gives for I. about 4200 meters; for III. about 6300 meters.

If the more probable supposition be made, that the rocks are porous, and therefore that the cavities are supported by the hydrostatic pressure of a column of water extending to the surface, it is necessary to subtract 1 from the specific gravity of the rocks, and the effective pressure is 1.7 grams per cubic centimeter. Applying Professor Hoskins' solution, the question is reduced to finding the height of a column 1 square centimeter in area, with a specific gravity of 1.7, which weighs two-thirds of 1700 kilograms for Conclusion I., and weighs 1700 kilograms for Conclusion III. This gives for I., 6667 meters, and for III., 10,000 meters. For the very strongest rocks the above numbers should perhaps be increased by one-fifth, and this gives a maximum of 12,000 meters.

These conclusions do not apply to rock-inclosed, liquid-filled cavities. So far as one can understand the conditions, such cavities might exist at an indefinite depth, or at least to a depth where the liquid and rock may be miscible in all proportions.

The above numbers fall within the various limits—roughly, 2 to 8 miles—assigned for the “level of no strain,”¹ or as it should perhaps be called more properly the level of no lateral stress, and thus make it probable that the lateral stress is less than the vertical stress of gravity. Therefore it is probable that the conditions upon which Conclusion III. are based more nearly represent the truth for the greater part of the earth

¹*Manual of Geology*, by JAMES D. DANA, 4th ed., 1895, pp. 384, 385.

than do those of Conclusion I. However, in mountain-making regions the lateral stress may be so great as to comply with the conditions of Conclusion I., and therefore cavities may close at the minimum depth.

The maximum result reached by the calculation is probably in excess of the truth, for all of the assumptions excepting that concerning the free escape of water are those favorable to requiring a great depth for the closing of cavities. However, it is believed that the result is valuable, because it is certainly large enough, and we may be sure that at depths greater than 12,000 meters no cavities can exist. Also it is reasonably certain that in the weaker rocks cavities are closed much nearer the surface than this. As more accurate data for the solution of the problem become available, it may be possible to obtain reasonably accurate results for the rocks of greatest strength and also for weaker rocks of different kinds. For instance, if the crushing strength of ice be determined for temperatures at and somewhat below zero centigrade, the greatest possible depth to which crevasses in glaciers extend at such temperatures may be readily calculated.

It is highly probable that the very greatly increased plasticity of rocks when saturated with superheated water, due to the rise of temperature with depth, would lead to the closing of the deeper lying crevices by flowage and welding rather than by fracture. If the increase in temperature is 1° C. for 30 meters, at a depth of 10,000 meters, the material would have a temperature of 333° C. above the average temperature of the level where climate produces no influence. To this, in mountain-making regions, would have to be added any increase in temperature due to dynamic action. Under gravity alone rocks at such a depth would be subjected to a vertical pressure of 2550 kilograms per square centimeter. As has been seen, the lateral pressure might be less than this if the rock was not in mountain-making areas and near the level of no lateral stress, or it might be as much or more than this if in mountain-making areas and therefore subjected to great lateral pressure. It is probable that at

such temperatures and pressures even brittle rocks, under these great and very slowing acting forces, when saturated with superheated water, obey the laws of hydrostatics, for plastic solids when strained beyond the limit of elasticity follow the same laws of deformation as do liquids. It is probable that the above considerations should reduce the estimate for the closing of cavities in the strongest rocks to 10,000 meters or less.

It therefore appears highly probable that at a depth of 10,000 meters not only do no crevices permanently exist in the earth, but the rocks are in such a condition that actual welding of the fractured parts would soon take place, supposing fracture to occur.

Such was apparently the case in the deepest lying gneisses and anorthosites of the original Laurentian area, described by Adams.¹ Here in certain areas each of the individual mineral particles is broken into many fragments. No extraneous or infiltrated material is discovered between the granules, and yet the rocks are exceedingly strong and tough, showing in all probability that the broken particles were welded. However, there may possibly be a zone in which the deformation occurs by minute fractures of the individual particles, these being held together without interspaces, and yet where the temperature and pressure are not sufficient to cause welding.

The conclusions as to the depth at which cavities close accord well with observations in the field and with the microscope. It is only in material from the cores of great mountain masses or in regions subjected to vast denudation that the microscope is unable to discover crevices caused by great deformation. The large secondary cracks and crevices which may have formed during the time when the rocks were nearing the surface by denudation are not here referred to, but the innumerable minute crevices affecting the individual grains, which were plainly produced by the deep-seated deformation of the rock. In many instances in which such crevices are found it appears probable from the geology of the region that the rocks were buried under

¹A Further Contribution to our Knowledge of the Laurentian, by FRANK D. ADAMS. Am. Jour. Sci. (3), Vol. L., 1895, pp. 62, 63.

well-nigh 10,000 meters of material, although this is difficult to demonstrate.

Whether rocks flow or fracture is in many cases largely dependent on the rapidity of deformation. As pointed out by Professor Hoskins, a rock under a certain pressure in two directions, when rapidly deformed by a greater pressure in a third direction, may be fractured, and when less rapidly deformed may flow. This results from the fact that the elastic limit of a rock is always less than its ultimate strength. During the time of rapid deformation the rock may be fractured and crevices and cracks formed which are subsequently closed by plastic flow even if the stresses decrease in amount. Also, as the stresses were slowly increasing, there may have been very considerable flowage before any fractures were produced. Hence, even in homogeneous rocks, the zone of fracture and the zone of flowage are not sharply separated from each other, and the upper part of the zone of flowage is at different depths under varying conditions of stress. This principle is illustrated by the distortion of rocks in ancient buildings and by slabs of marble suspended by their ends in cemeteries.¹ This latter case shows how important the element of time is in the deformation of rocks, and that, given a sufficient time, a stress much below the ultimate strength may surpass the elastic limit and result in flowage. It thus becomes clear that there may be a very considerable thickness for any given rock in which it may be in the zone of fracture or in the zone of flowage, depending upon the amount of differential stress.

(3) *Rocks buried to such a depth that the weight of the superincumbent strata exceeds their ultimate strength are in the zone of plasticity and flowage.* These are the conditions of folding, for permanent perfect flexure is possible only by flowage of material. It is a contradiction to suppose that cracks and crevices can form under these conditions. Were it possible for an opening to be made in any way, under the hypothesis the rock would

¹ An Illustration of the Flexibility of Limestone, by ARTHUR WINSLOW. Am. Jour. Sci. (3), Vol. XLIII., 1892, pp. 133, 134.

flow toward the opening and close it. All of the rocks concerned are everywhere under compressive stress. The material at any given moment, when deformed, moves from places of great compression to places of less compression. In other words, there is always a tendency for the rocks to approach equilibrium through the forces applied, or to obey the laws of hydrostatics. In order that deformation shall occur, the difference between the greatest and the least stresses must equal or surpass the elastic limit of the rock in question under the conditions in which it exists. In rocks which were bent when so deeply buried that no cracks or crevices could form even temporarily, it is probable that the material flowed to its new position quietly, without shock, under the enormous stress to which it was subjected.¹

Even if in the zone of flowage, the relative thickness and strength of the members folded will play their part. If the mass were exactly homogeneous it would flow in the direction of least resistance, like a mass of tallow. But the rock masses are heterogeneous, and the alternating layers of different plasticity may retain their individuality, there being no considerable commingling of the materials of one layer with the materials of others. The strong, thick beds will greatly vary the direction of movement of the material at a given place, and thus, as explained by Willis, develop folds of great length and amplitude. On account of their relatively resistant character when bent into anticlines and synclines, the anticlines will be able to carry part of the superincumbent load, and thus relieve to some extent the softer beds below, which however, as a consequence, promptly flow in the direction of relief or least resistance and ever press against the confining arch, and thus do their part, which may be the major part, of carrying the superincumbent load. In a similar manner

¹ The manner of the molecular rearrangement by which flowage is accomplished will not here be discussed. In some cases of extreme deformation the granulation or even the recrystallization of the rock is complete. In intermediate cases strain effects are usually marked. For the present purposes we are concerned with the larger deformation of the rock masses. Even were the deformation accomplished wholly by minute fractures without crevices, the deformation in mass, would appear to be that of a plastic body.

the strong formations bent into synclines because of the thrust transmitted along their limbs furnished in part by the weight carried by the adjacent anticlines, will give increased pressure to the softer beds below and add to the ordinary thrust which is already forcing the material to follow the arches of the adjacent anticlines. However, if the superincumbent strata be but sufficient, the strongest and most brittle rock beds, such as quartzite and jaspilite, may be crumpled or bent upon themselves within their own radius without macroscopic sign of crevice or fracture. In extreme cases the microscope is unable to detect any evidence of crevices or cracks, but it shows in a most remarkable manner that the mineral particles have been greatly flattened.

The thinner and softer the beds the less potent are they to control the movement of any considerable amount of material. Therefore, under given conditions, the thinner and softer the beds the shorter and the steeper are the folds, and more nearly does their material approach in its movement to the flowage of tallow. In soft homogeneous shales the approximation is closest. Therefore, in a series or group of beds of different lithological characters, the thick, strong beds are less closely folded than the thin, weak beds. The softer layers are greatly thickened here and greatly thinned there, as demanded by the stronger layers. The folding of the first may be comparatively simple, and the second may be closely plicated. These principles are finely illustrated in the Hiwassee section of the Ocoee series of the southern Appalachians.

In any great anticlinorium, even if the strongest rock be at the bottom—for instance, a massif of granite—it yields to the force of thrust under the law of normal plastic flow, moving toward the places of least compression, and ever presses against and helps to raise and support the overlying arch of sedimentary and other rock. If a massif were absolutely homogeneous without reference to its strength, its movements would be analogous to that of wax. Consequent upon such movement, as explained in a subsequent paper, it is believed that uniform cleavage is often produced. But no massif is homogeneous. It is composed of

mineral particles of different kinds and of different sizes. In a larger way it is composed of rock masses of different characters. Frequently these masses of different characters and strength are divided by vertical or steeply inclined planes of weakness, rather than horizontal ones, as in the sedimentary rocks; hence, major movements take place along the major inclined planes and minor movements along minor planes and between the mineral particles. Complex minor folding and shearing therefore occur in the readjustment of a massif to its new position. The major planes of shearing may be called fault planes, but they differ from ordinary faults in that the parts moved over one another are always in close contact, and probably are also always welded.

When a set of rock beds are bent even slightly, readjustment and rearrangement of the material must occur to some extent, and the amount increases in proportion as the rocks are closely folded.

If a steel bar be bent the molecules are separated to some extent upon the convex side and compressed upon the concave side. When released from stress the bar, by virtue of elasticity, springs back to its original position. While to some slight degree rocks are elastic when subjected to forces continuing for a short time, it may be doubted whether this property is of importance in considering the slowly acting and long-continued forces of rock folding, except perhaps in the slight flexures of great extent. Single rock beds, when much deformed, are rather to be compared to a wrought-iron bar, which when bent takes a permanent set. In this case there is an actual flowage of material or rearrangement of the particles to meet the new conditions. The half of the bar on the convex side subjected to tension is lengthened, and, to compensate, it is of less cross-section than originally. The half of the bar on the concave side subjected to compression is shortened, and, to compensate, it is of greater cross-section than originally. Each homogeneous rock stratum when bent acts like the iron bar to a certain extent. There is rearrangement of its material to new positions, and when the bending occurs without fracture the movements of the rock particles may be like those of the par-

ticles of the compressed part of the iron bar. But rock beds are usually composed of different mineral constituents, which differ from one another in strength, in hardness, in brittleness, in elasticity, and in size. The necessary rearrangement of the mineral particles more largely affects the weak, small particles than the large, strong ones. However, as shown by microscopical study, where a district is closely folded, no particle of a rock stratum, small or great, simple or complex, weak or strong,

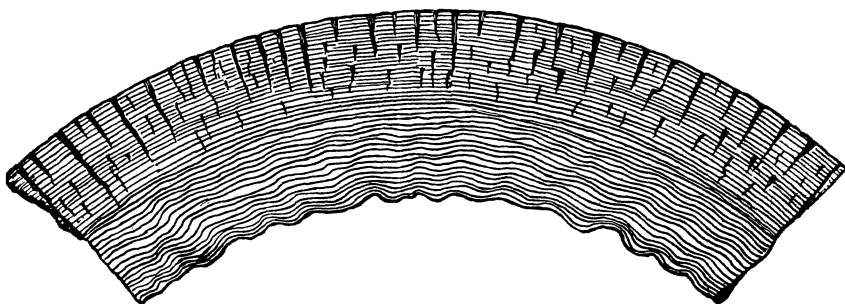


FIG. 1.

escapes the effects of, or fails to take part in, the necessary readjustment of folding.

If a rock stratum could be bent without fracture in such a position that the superincumbent weight were slight, about one-half of the bed, like the iron bar, would be elongated, and the other half would be compressed. Between the two there would be a neutral plane.

As rock beds are brittle they act differently from an iron bar when bent to any considerable degree. Beginning at the middle of the mass in the trough or crest of the fold and passing toward the convex surface, the first lamina is under tension, the second under greater tension, and so on, each stratum being stretched more than the preceding. The tensile force may go beyond the limit of elasticity and radial cracks be formed. (Fig. 1.) Beginning again at the center and passing toward the concave surface, the first layer is under compression, the second under greater compression, and so on, each stratum being more severely squeezed

than the preceding. This may go beyond the limit of elasticity and produce minor plications.

But the majority of strata which have been closely folded when bent were deeply buried beneath other strata. If the superincumbent weight was greater than the strength of the rock all parts of it were under compression, increasing, it is true, from top to bottom in an anticline, and if the mass is not too thick from bottom to top in a syncline. In this case there was no

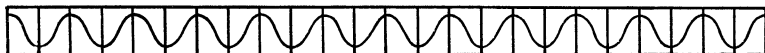


FIG. 2.

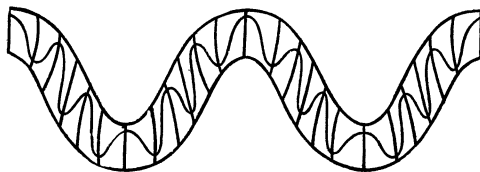


FIG. 3.

neutral plane. The rearrangements which took place were therefore those of varying compression,—flowage away from the places of greatest compression and flowage toward the places of least compression. The crenulations in an anticline may mean that the part of the fold seen was in the compressed area, the stretched and fractured part being removed by erosion. Where both the anticlines and synclines show plications throughout, it follows that the superincumbent strata were so thick that no zone of stretching could be formed, the weight being beyond the supporting strength of the rocks, and the movements being those of a heterogeneous plastic body.

Just as there is rearrangement of the particles within a bed, so there is readjustment of the beds over one another. This may be illustrated by a bunch of paper. (Figs. 2 and 3.) If straight lines be drawn at the edges of a bunch of horizontal sheets, and then the whole be bent into folds, it will be found that the straight lines become curved. In other words, the sheets were moved over one another. An examination of the curved lines

shows that on opposite sides of an anticline or syncline the movement for any given stratum is in opposite directions. Therefore at the anticlines and synclines the forces are directly opposed and hence the stretching or plications at these places, as already explained. But on the limbs of the folds the forces are in the same direction for each lamina, but in opposite directions for laminae upon opposite sides of any layer, thus constituting a couple. Each stratum moves up as compared with the one next below it, and each stratum moves down as compared with the one next above it. In the case of much inclined and overturned folds this statement needs modification.

The axial lines also show that on the crests of the anticlines and in the troughs of the synclines there was comparatively little movement, while at the middle of the limbs of the folds movements were at a maximum. From this experiment and from Figs. 4 and 5 we would expect that in folded rock strata the effects of readjustment would be least at the crests of the anticlines and troughs of the synclines and most at the middle of the limbs, and such are the facts. In a subsequent article it will be seen that clastic rocks become crystalline in proportion to the degree of shearing and the intensity of the pressure. The former is at a maximum on the limbs of folds and at a minimum on the crests and troughs. Further, secondary structures may develop on the limbs nearly parallel to the beds, while upon the anticlines and synclines the secondary structures form across the beds. It follows that on the anticlines and synclines, where there is most crenulation and puckering of the laminae, the original structures are less altered, and the clastic characters in sediments, such as sandstones and conglomerates, are likely to be preserved. Upon the other hand, upon the limbs of the folds the obliteration of fragmental characters may be complete. We therefore have the paradox that where there is most crenulation there is least metamorphism; where least crenulation, most metamorphism. This of course applies only to the different positions of the rock in a fold, not to a gently folded district as compared with a more closely folded area.

But the rock beds as they occur in nature differ from the bunch of paper in that they are of varying thickness and strength. The major readjustments of the rock beds occur between the thick and strong strata, and within the weak and soft strata. In these latter, therefore, the rearrangement of the particles is far more profound than would be the case if such beds were folded alone. In closely folded districts among other evidence of readjustments the polishing effects of accommodation between the beds may always be seen in the slickensided surfaces of the major and stronger beds, and in cases of complicated folding the same phenomena are observable between the thinnest laminæ. A most striking instance of this polishing is seen in the Jura Mountains, where at many places both sides of the strong, thick layers of Jurassic limestone are polished as smoothly as if glaciated. They reflect the sun like an imperfect mirror. At some places where the folds are steep, layers have fallen down along these movement planes, exposing great surfaces of beautifully polished rock. In the folded Cambrian quartzites of Doe River, Tennessee, the polishing of the layers by accommodation is scarcely less strikingly illustrated.

If a given bed in the center of a rock formation be plicated and the layers above and below be folded in a strictly parallel manner, in passing away from the central bed in either direction those on either side are less closely folded, and finally the crenulations become slight. If the folds are close in the center they die out with great rapidity. The above follows directly from the laws of deformation of solid masses, and is illustrated by Fig. 4. It should be observed that the more crenulated lines are longer than the less crenulated ones. In so far as this is imitated in nature this implies that there is differential movement between the layers, for originally all of the beds must be supposed to have been of the same length. Such differential motion doubtless does occur in strata in which the folds differ in character, for the more closely folded beds must be subjected to severer thrusts or have been originally weaker, so that the thrust is more effective, or have been in a position in-

which friction gave less resisting power. The ideal figure probably more nearly illustrates the effects of nature in passing downward from the central line than in passing upward, for the deformation in superficial strata may be accomplished by jointing, faulting, and brecciation.

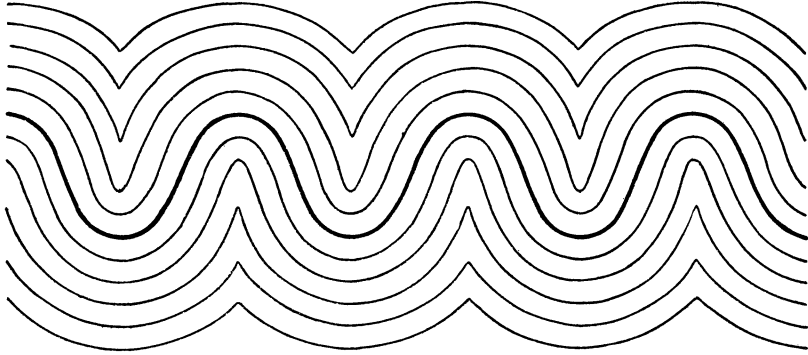


FIG. 4.

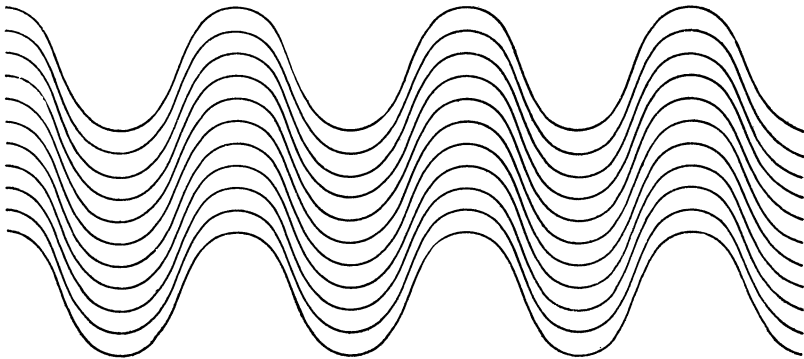


FIG. 5.

If beds above and below the central one be folded in a similar fashion, the limbs of the different layers will be closely pressed together or thinned, or both, and at the anticlines and synclines there will be spaces between the layers, or thickening, or both (Fig. 5). But this result can only be accomplished by plastic flow of the material of the limbs toward the areas of relief. This often produces minor plications at the crests and troughs. Even where the folding is only moderately close the limbs of folds

may be only one-half as thick as the troughs and crests. Where the folding is very close the troughs and crests must be several times as thick as the limbs in order that they may have similar forms.

It is evident from the above that close folds can persist in depth with similar forms only by great differential movement of material, for the readjustment will only go so far as demanded by the differential stresses. It is therefore to be expected that the close folds of mountain districts die out rapidly with increasing depth. This would certainly be true if the lateral stresses diminish, as they must do if the theory of "level of no strain" at very moderate depth be correct. The foregoing doubtless partly explains the open folding often observed in the center of the mountain masses as contrasted with the closely folded flanks, although in many cases other causes undoubtedly enter.

This rapid disappearance of folds with increased depth is beautifully illustrated in a section along the Schuylkill River near Philadelphia, between Lafayette and Spring Mill, shown me by Miss Florence Bascom. In the center of the section is gently undulating gneiss. In passing toward the outer part of the gneiss it is closely folded. The gneiss is flanked on either side by still more closely folded mica-schist. Not only is the principle illustrated by the entire section, but at various places close local folds may be seen, above and below which the folds rapidly become more open. The same is illustrated in the crumpled gneisses of the Ottawa River. The same principle is illustrated upon a much larger scale by the section along the Doe River west from Cranberry, N. C. The folding and the schistosity of the pre-Cambrian granitoid gneisses are gently composite, while the overlying Palæozoic quartzite shows many close minor folds. This case is a particularly good one, for it can hardly be supposed that the quartzite is much less rigid than the gneissoid granite.

It follows from the above that where different beds are in folds of similar forms rearrangement within the beds, adjustment between the beds, and distortion of the beds all work together

to shear the limbs of the folds parallel to the bedding and to develop plications in the crowns and troughs.

(2) *Since the boundary between the zone of fracture and the zone of flowage is at a different depth for two rocks of unequal strength, and for the same rock under different conditions of stress, there is a zone of combined fracture and flowage.* In a set of heterogeneous beds upper weak strata may be in the zone of folding, while lower and stronger strata may be in the zone of fracture. Also, as pointed out by Willis, if strong folded strata at anticlines are competent to carry much of the load, as they often are if the arches are not too long, weaker strata below may be so relieved from weight as to be partly deformed by fracture. Thus between the horizon where all the rocks of a district fracture, notwithstanding the weight of the superincumbent beds and the horizon where the effective weight of the superincumbent beds, is so great that no rock fractures is a zone of combined folding and fracturing. This central zone is one of great thickness, and is of the first importance.

A soft shale may be in the zone of folding, far above a strong quartzite or jaspilite, and the latter be in the zone of partial deformation by fracture. This difference in strength is at many places certainly equal to the weight of 2000 or 3000 meters of strata, and is probably equal to the weight of 5000 or more meters of strata. Thus this middle zone is probably at least 5000 meters thick, and it may be considerably thicker than this.

In heterogeneous rock strata in this middle zone, irregular fracturing, brecciation, jointing, faulting, folding and the development of secondary structure may occur together in a most complex manner. A deeply buried, brittle formation may be under such stress that as a whole it folds without major fracturing, but in a minor way it may be faulted, fractured, or brecciated. The fracturing may leave no permanent openings, as the softer material may promptly flow and fill the openings between the more brittle broken layers. Such is the case in the jaspilite beds of the Lower Marquette series of Michigan. Such is also the case at many places where beds of shale or limestone

are interstratified with beds of grit or sandstone. The first may pass to its new position by homogeneous flow, the second by repeated fractures, which in extreme cases may break the harder beds into fragments and bury them in the softer rocks. The same relations often are seen between mobile marble and brittle gneiss. Whether fracturing always implies at least temporary crevices is an undetermined point.

The weight of the superincumbent material may have been so great that the rock beds as a whole bent without macroscopic fracture, and yet the microscope may show that the individual grains were broken and that minute crevices were formed which have been subsequently filled by secondary infiltrations. At many places the massive beds the quartzites of Doe River, Tennessee, are bent upon themselves within their own radius, with no macroscopic evidence of crevice or fracture. But the microscope shows that the fracturing and resultant flattening of the quartz grains was almost universal.

This illustration shows that for a given kind of rock the zone of fracture passes gradually into the zone of flowage. Even where so deeply buried that all large fractures are absent and the rocks are practically in the zone of flowage, the microscope may still show crevices. It has already been indicated that the zone of flowage is much deeper for some rocks than for others. Also for the same rock mass it may be less deep when gently folded than when closely folded. It is therefore clear that there are gradations between the three zones—of fracturing, of fracturing and flowage, and of flowage. In the placing of a rock mass in one of the three zones it is to be considered as belonging to the one to which it most closely corresponds. If the rocks are everywhere broken and show comparatively little folding, they are in the zone of fracture; if they show much fracturing and also are folded, they are in the zone of fracture and flowage; if the fractures are subordinate or microscopic, they are in the zone of flowage.

C. R. VANHISE.